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LIFE CYCLE MANAGEMENT

Combining risk assessment, life cycle assessment, and multi-criteria decision analysis to estimate environmental aspects in environmental management system

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Abstract

Purpose The rating of environmental aspects plays a central role in the ISO 14001 environmental management system (EMS) and EU Eco-Management and Audit Scheme because it is the basis for the identification of an organization's environmental targets. The existing methods for the assessment of environmental aspects are grouped into three categories: risk assessment-based (RA-based), life cycle assessment (LCA)-based, and criterion-based methods. The first category accurately determines abnormal, or accidental aspects, as well as the probabilistic causality of aspect–pathway–receptor–impact relationships, but when evaluating environmental impact, it cannot provide a sound theoretical basis. The second category provides a theoretical foundation for the assessment of environmental impact, due to LCA, but cannot adequately represent the probabilistic aspect–pathway–receptor–impact relationship. The third category puts emphasis on the significance criteria, but the scoring methods are too simple. To combine the benefits of these three categories of research, this study proposes an integrated framework, combining RA-, LCA-, and criterion-based methods.

Materials and methods The integrated framework incorporates LCA techniques for the identification of the causal linkage for aspect–pathway–receptor–impact, uses fuzzy logic to assess aspects, considers fuzzy conditions, in likelihood assessment, and employs a new multi-criteria decision analysis method—multi-criteria and multi-connection comprehensive assessment (MMCA)—to estimate significant aspects in EMS.

Results and discussion The proposed model is verified, using a real case study—a waste-recycling factory. The results show that this method successfully prioritizes the environmental aspects. Compared with criterion-based methods, the case study demonstrates that the proposed method provides a more solid theoretical basis.

Conclusions This study integrates RA, LCA, and MMCA, to assess environmental aspects. The method identifies the probabilistic causality of aspect–pathway–receptor–impact relationships, enhances the theoretical foundations, and strengthens decision-making.

Keywords Environmental aspect · Environmental management system · Fuzzy comprehensive assessment · Fuzzy logic · Life cycle assessment · Multi-criteria and multi-connection comprehensive assessment · Risk assessment

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1 Introduction

Environmental management system (EMS) is used by an organization to develop and implement its environmental policy and to manage its environmental aspects. An environmental aspect is defined as an element of an organization's activities, products, or services that can interact with the environment; an environmental impact is defined as any change to the environment, whether adverse or beneficial, wholly or partially resulting from environmental aspects (ISO 14001:2004). An environmental aspect is considered to be significant, when it has, or can have, a significant environmental impact. The key to a successful EMS is the proper identification and evaluation of environmental aspects and their potential impacts because the most significant environmental aspects play a crucial role in the formulation of effective environmental policy, in terms of the definition of objectives and targets, therein providing the basis for the entire EMS (Põder 2006). However, EMS does not provide a method for the assessment of environmental aspects, only some general guidelines. The methodological issues associated with the evaluation of aspects have been largely overlooked (Põder 2006).

An overview of the assessment of significant environmental aspects is illustrated in Fig. 1.The critical elements are aspects, exposure pathways, receptors, and impacts. Receptors are considered because impacts vary, according to different receptors, and further investigation of the impact is not required, if no receptor or pathway exists. The causal linkage for aspect–pathway–receptor–impact can be identified through methods such as causal network analysis (Monavari and Fard 2011), life cycle assessment (LCA), etc. It should be noted that an environmental aspect may cause several impacts and, sometimes, one impact can induce another. Once the cause–effect relationships are identified, a four-stage assessment is proposed, as follows (see Fig. 1): Firstly, the assessment of an environmental aspect includes its frequency, scale, duration, magnitude, etc. Secondly, the likelihood assessment of an environmental impact has two components: the probability of a receptor being exposed to the aspect and the probability of an impact resulting from exposure to the aspect. Thirdly, an environmental impact is assessed based on its scale, duration, severity, etc. Fourthly, the significance assessment covers the selection of significance criteria and the prioritization of environmental aspects/impacts, according to those criteria.

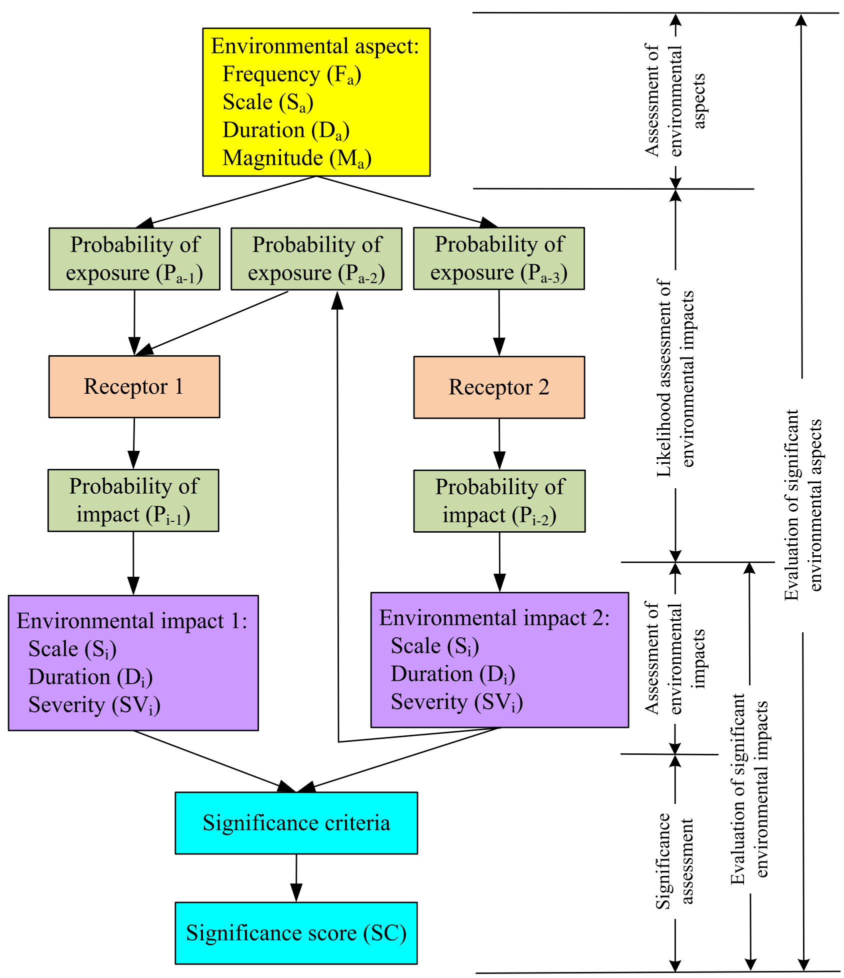


Fig. 1 Overview of the assessment of significant environmental aspects

Related work on the assessment of environmental aspects in EMS can be divided into three categories, as shown in Table 1. The first category employs risk assessment-based methods, to estimate the values of the frequencies or probabilities, scales, durations, and severities of environmental aspects/impacts. Most researchers in this category use the multiplication of these values as the scoring method for the identification of significant aspects/impacts. These studies use risk assessment (RA), which can accurately identify abnormal or accidental aspects, as well as the probabilistic causality of aspect–pathway–receptor–impact relationships. However, when evaluating the severity of an environmental impact, most lack a sound theoretical basis and tend to be over-subjective.

Another category of research advocates enhancing the theoretical foundation for the assessment of the severity of environmental impacts, by utilizing LCA-based methods. Although these LCA-based methods can provide global and regional scales for environmental impact, they cannot adequately represent abnormal or accidental aspects and the probabilistic aspect–pathway–receptor–impacts relationships. The third category puts emphasis on significance criteria, such as socioeconomic factors, legal requirements, cleaner production opportunities, control of aspects, and the concerns of interested parties. In Taiwan, most of the methods used in the business practice fall into this category. Although they consider more factors in determining significant aspects/impacts, their scoring methods do not use a more sophisticated decision theory, such as multi-criteria decision analysis (MCDA), but use simple addition, multiplication, or linear combination.

This study combines the benefits of the three categories of research by integrating RA-, LCA-, and MCDA-based methods, to identify the probabilistic causality of aspect–pathway–

Table 1 Related work on the assessment of environmental aspects in EMS

	Related work	Aspect assessment				Likelihood assessment		Impact assessment			Significance assessment (other significance criteria)	Scoring method
		F_a	S_a	D_a	M_a	P_a	P_i	S_i	D_i	SV_i		
RA-based method	Burke and Gaughran (2006)	•					•			•		Multiplication
	Edalat (2008)					•	•			•		Multiplication
	Gangolells et al. (2009)						•	•	•			Multiplication
	Zorpas (2010)	•					•			•		Multiplication
	Moraes et al. (2010)	•								•		Decision table
LCA-based method	Zobel et al. (2002, 2004)									•		
	Zackrisson (2005)									•		
	Gernuks et al. (2007)									•		
	Lewandowska (2011)									•		
Criterion-based method	Põder (2006)						•			•	Socioeconomic factors	Linear combination
	Seiffert (2008)	•								•	1. Legal requirement 2. Cleaner production opportunity 3. Interest party demand 4. Strategic options 5. Existing control	
	Chen (2009)	•								•	1. 1. Technology 2. Cost 3. Public image 4. Safety and health	Decision table and multiplication
	Marazza et al. (2010)	•	•							•	1. Control; management 2. Increased sensitivity factors 3. Participation and public feelings	Linear combination
	Ljubas and Sabol (2011)	•								•	1. Control of aspect 2. Legal exposure 3. Public exposure	Addition and multiplication
	Gangolells et al. (2011)									•	Concerns of interested parties	Multiplication

• considered

receptor–impact relationships, to enhance the theoretical foundation and to strengthen decision-making. This integrated framework incorporates LCA techniques for the identification of the causal linkage for aspect–pathway–receptor–impact, uses fuzzy logic for the assessment of aspects, considers fuzzy conditions, in likelihood assessment, and employs a new MCDA method—multi-criteria and multi-connection comprehensive assessment (MMCA)—to estimate the significant aspects in EMS. Finally, a waste-recycling factory is as a case study, in order to demonstrate the use of the method.

2 Case study

A small waste-recycling factory, covering about 1.14 ha, is located in Taichung County, Taiwan. It recycles 35.57 t of construction waste per year and turns it into combustible waste, wood, metal, recycled soil, recycled fine aggregate, recycled coarse aggregate, PVC plastics, and rubber tires. The construction waste is processed using many machines, such as a trommel screen, a winnowing machine, a crusher, a backhoe, a hopper, a conveyor, and a transportation vehicle. Recently, this factory is preparing for ISO 14001 certification. Environmental aspects in ISO 14001 are defined as the elements of an organization's activities, products, or services which can interact with the environment. The full version of the environmental aspects involves 66 items (Electronic Supplementary Material 1), spanning from air pollution, noise, water use and nonrecyclable waste, to nonrenewable energy consumption. However, the printed version of the paper is subject to page limits so that only 20 environmental aspects, which are selected from the top 20 in the final results (see Electronic Supplementary Material 7), are discussed (Table 2) and most of them are related to the generation of noise or the emission of total suspended particulates (TSP).

3 Integrated framework

The integrated framework, combining RA-, LCA-, and MCDA-based methods, comprises the following steps: (1) incorporating the LCA concept for the identification of the causal linkage of aspect–pathway–receptor–impact, (2) using

Table 2 Selected environmental aspects and their severity evaluations, for a waste-recycling factory

No.	Environmental aspect	Category	M_a	S_a (m^2)	D_a (year)	SE$_a$	SE$_{SV}$	SR$_a$
a-1	A3 918 trommel screens generate TSP	Air pollution	9.57 (mg/m^3)	84.95	0.333	7.00	70.8	9.89^{13}
a-2	A3 918 trommel screens produce noise	Noise	67.45 (dB(A))	15,386	0.333	46.67	70.8	$\underline{65.92}^{4}$
a-4	A5 winnowing machines cause noise	Noise	69.21 (dB(A))	20,096	0.333	48.17	70.8	$\underline{68.04}^{2}$
a-5	A5 winnowing machines generate TSP	Air pollution	9.66 (mg/m^3)	84.9	0.333	7.02	70.8	9.91^{11}
a-7	A7 crushers generate TSP	Air pollution	4.83 (mg/m^3)	38.9	0.333	6.14	70.8	8.68^{14}
a-13	B2 125 trommel screens produce TSP	Air pollution	9.66 (mg/m^3)	84.9	0.333	7.02	70.8	9.91^{11}
a-14	B2 125 trommel screens generate noise	Noise	67.45 (dB(A))	15,386	0.333	46.67	70.8	$\underline{65.92}^{4}$
a-16	B3 winnowing machines produce noise	Noise	69.21 (dB(A))	20,096	0.333	48.17	70.8	$\underline{68.04}^{2}$
a-17	B3 winnowing machines cause TSP	Air pollution	4.83 (mg/m^3)	38.4	0.333	6.14	70.8	8.68^{14}
a-19	Transporting and dumping materials by vehicles produce TSP	Air pollution	88.73 (mg/m^3)	1,017	0.333	17.65	70.8	24.93^{8}
a-25	Normal operation of backhoes produces noise	Noise	72.21 (dB(A))	31,400	0.333	53.20	70.8	$\underline{75.14}^{1}$
a-26	Normal operation of backhoes causes TSP	Air pollution	2.88 (mg/m^3)	22.06	0.333	5.78	70.8	8.16^{18}
a-32	Digging mixtures into hoppers by backhoes generates TSP	Air pollution	4.83 (mg/m^3)	38.93	0.333	6.14	70.8	8.68^{16}
a-34	Drying moving lines by drying vehicles generates TSP	Air pollution	2.88 (mg/m^3)	22.06	0.333	5.78	70.8	8.16^{18}
a-40	Stirring up finished or semifinished products in storage area causes TSP	Air pollution	163.67 (mg/m^3)	1,963	0.333	23.01	70.8	32.49^{7}
a-42	Loading or transporting finished or semifinished products generates TSP	Air pollution	59.15 (mg/m^3)	624.58	0.333	14.41	70.8	20.36^{9}
a-48	Removal and transportation of plastic waste produce TSP	Air pollution	1.44 (mg/m^3)	12.57	0.333	5.51	70.8	7.78^{20}
a-54	Transporting debris by conveyor causes TSP	Air pollution	4.83 (mg/m^3)	38.4	0.333	6.14	70.8	8.68^{16}
a-57	Transporting finished or semifinished products by scrapers produces TSP	Air pollution	29.58 (mg/m^3)	314	0.333	10.33	70.8	14.59^{10}
a-63	Friction between bucket and ground friction produces noise	Noise	66.45 (dB(A))	13,267	0.333	45.81	70.8	64.71^{6}

Superscript denotes the sequence order

fuzzy logic for assessing the severity of environmental aspects, (3) applying a severity ratio, to compare with standard values, (4) estimating the probability of the receptors being exposed to an aspect, (5) evaluating the probability of an impact being exposed an aspect, (6) using the vertex method to compute the risk of the impact, and (7) employing the MMCA to establish significance criteria and prioritize environmental aspects, accordingly (Fig. 2).

3.1 Incorporating the LCA concept, to identify aspect–pathway–receptor–impact

The starting point for the evaluation of the significance of an environmental aspect is to identify the possible exposure pathways (midpoint effects) and the subsequent impacts (endpoint effects), caused by the environmental aspect, and thereby to determine the importance of the impacts. Existing LCA methods provide such a basis for the identification of the cause–effect relationship between aspects, exposure pathways, receptors, and impacts. This version of the cause–effect relationship for the identification of aspect–pathway–receptor–impact uses a three-step procedure, as follows.

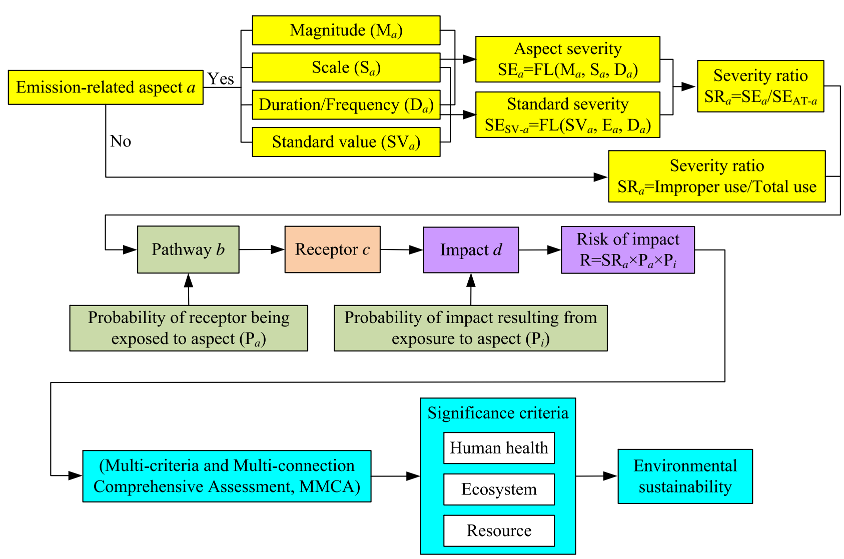
1. Identification of environmental aspects: The environmental aspects are roughly divided into two groups: emission-related or non-emission-related, as shown in part A of Fig. 3. The emission-related aspects usually are those contaminants with the nature of diffusion, whereas the non-emission-related aspects are those such as the use of water, nonrenewable energy and raw materials, and the generation of nonrecyclable waste.
2. Identification of pathways: Prior to determining significance, a diagram of the causal relationships between environmental aspects and receptors that includes all the relevant pathways allows stakeholders to understand the midpoint effects of a pollution emission, as shown in part B of Fig. 3. An environmental aspect may cause several midpoint effects. For example, N_2O can induce climate change and stratospheric ozone depletion, simultaneously. On the other hand, N_2O, CO_2, CH_4, PFCs, or SF_6 can also cause a rise in temperature and a potential rise in sea levels, with the risk of flooding.
3. Identification of receptors and their possible impacts: The types of impacts brought about by a midpoint effect depend upon receptors, as shown in parts C and D of Fig. 3. For example, climate change might lead to human malnutrition, infectious diseases, heat stress, and the loss of biodiversity in ecosystems, resulting in the decreased production of crops and wood.

3.2 Using fuzzy logic for aspect assessment (SE_a)

The severity of an emission-related environmental aspect (SE_a) is determined by its magnitude (M_a), scale (S_a), and duration (D_a). The magnitude refers to the concentration of a pollution source, usually measured in parts per million, milligrams per liter, or milligrams cubic meter. The geographical scale is expressed as the area where the concentration at any point is higher than one third of its magnitude (M_a). The temporal factor is measured by the duration of the emission of the pollution, within 1 year.

Appraising the severity of an emission-related environmental aspect can be a subjective decision-making process and is performed using fuzzy logic (Zadeh 1996), in this study. Fuzzy logic can be thought of as a tool with the ability to compute with words, when modeling qualitative human thought processes, in the analysis of complex systems and decisions. Fuzzy logic uses qualitative perception-based reasoning, represented by "IF-THEN" fuzzy rules. The rule set concerning the evaluation can be described as in Table 3, where "magnitude," "scale," "duration," and "severity" are linguistic variables (Zadeh 1975) and "very low," "low,"

Fig. 2 Integrated framework



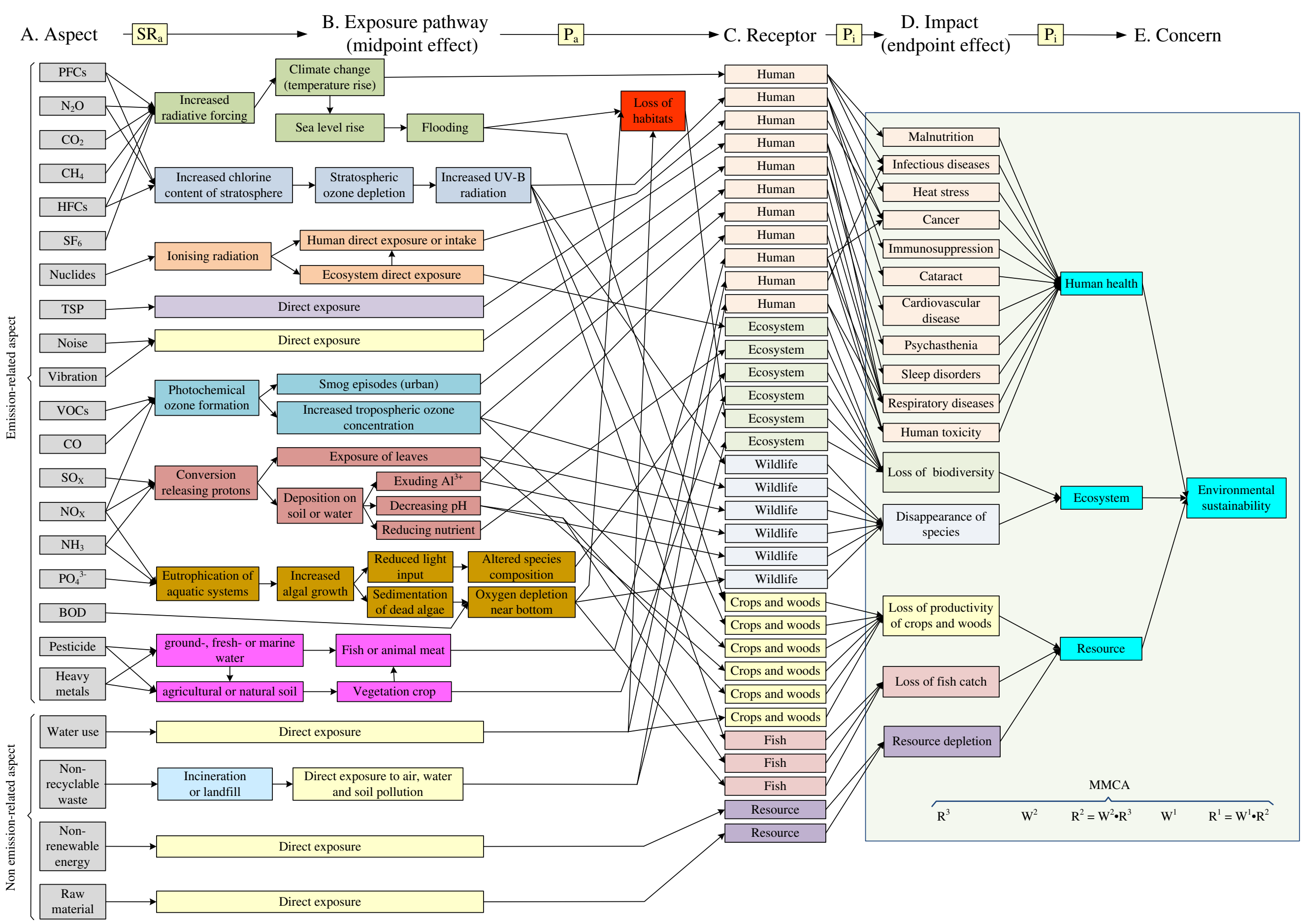


Fig. 3 Overview of the causal relationships between aspects, pathways, receptors, and possible impacts [modified from (Udo de Haes et al. 1999)]

"medium," "moderate," "high," and "very high" are the possible fuzzy values, which are defined by triangular fuzzy sets, as shown in Electronic Supplementary Material 2. A triangular fuzzy set can be expressed as a 3-tuple (l, m, r), where l, m, and r are the locations of the left, middle, and right peaks of the triangle, respectively. For example, low magnitude is expressed as (0, 0, 50) (Electronic Supplementary Material 2).

To evaluate the severity of emission-related environmental aspects, 19 rule bases, containing 513 fuzzy rules, were produced through the authors' discussion. The four authors specialized in environmental management and information systems. Furthermore, a trial and error process was involved in calibrating the fuzzy rules before finally arriving at a workable set of rules. These 19 rule bases and their corresponding membership functions were constructed, based on expertise, and the fuzzy inference systems were implemented with MATLAB Fuzzy Logic Toolbox. The fuzzy rule-based system in this study is validated via six criteria (Electronic Supplementary Material 3).

When assuming that three factual statements about aspect "*a*-25 normal operation of backhoes produces noise" in Table 2 (i.e., fact 1: the magnitude of the noise produced by the normal operation of a backhoe is 72.21 dB(A); fact 2: the spatial scale of the noise produced by the normal operation of a backhoe is 0.0314 km^2; and fact 3: the temporal duration of the noise produced by the normal operation of a backhoe is 0.333 year) are fed into this inference mechanism, fuzzy reasoning (Zadeh 1975) proceeds. The theory of fuzzy reasoning is detailed in Electronic Supplementary Material 4, but it is easily explained using a graphical representation, as shown in Fig. 4. In this figure, the four major steps to a conclusion, using fuzzy reasoning, are described as follows:

Step 1: Computing compatibilities

Compatibility defines the similarity of an antecedent, which refers to a fact having the same linguistic variable, or the suitability of a specific rule, with regard to several facts, corresponding to the respective antecedents. For rule 13, the compatibility of fact 1 with "the magnitude of the noise produced by the normal operation of backhoes is medium" is 0.556; for fact 2, its compatibility with "the

Table 3 Fuzzy rules for the evaluation of aspect severity

Rule no.	IF part			THEN part
	Magnitude	Scale	Duration	Severity
1	Low	Low	Low	Very low
2	Low	Low	Medium	Very low
3	Low	Low	High	Low
4	Low	Medium	Low	Low
5	Low	Medium	Medium	Low
6	Low	Medium	High	Low
7	Low	High	Low	Low
8	Low	High	Medium	Low
9	Low	High	High	Slightly low
10	Medium	Low	Low	Very low
11	Medium	Low	Medium	Slightly low
12	Medium	Low	High	Moderate
13	Medium	Medium	Low	Slightly low
14	Medium	Medium	Medium	Moderate
15	Medium	Medium	High	Moderate
16	Medium	High	Low	Moderate
17	Medium	High	Medium	Moderate
18	Medium	High	High	High
19	High	Low	Low	Moderate
20	High	Low	Medium	High
21	High	Low	High	High
22	High	Medium	Low	Moderate
23	High	Medium	Medium	High
24	High	Medium	High	Slightly high
25	High	High	Low	High
26	High	High	Medium	Slightly high
27	High	High	High	Very high

spatial scale of the noise produced by the normal operation of backhoes is medium" is 0.908; and for fact 3, its compatibility with "the temporal duration of the noise produced by the normal operation of backhoes is high" is 0.333. It should be noted that the "product" is chosen as the t-norm operator, rather than using another more widely used t-norm operator, "min," because the t-norm operator, product, renders the conclusion sensitive to every input, whereas only one input controls the conclusion in the case of the t-norm operator, min. The overall compatibility of rule 13 with the four facts is computed as $0.556 \times 0.908 \times 0.333$, which is 0.168. The compatibilities of other rules are calculated in the same way.

Step 2: Truncating conclusions

Once the compatibility for each rule has been calculated, the degree to which the antecedents have been satisfied for each rule is known. As shown in Fig. 4, a new conclusion is then inferred, by scaling the triangular conclusion of each rule with its corresponding compatibility. The use of the implication operator, product, results in the scaling of each conclusion.

Step 3: Aggregating truncated conclusions

Several inferred conclusions with the same linguistic variable must be aggregated. Aggregation is the process by which the fuzzy sets representing the scaled conclusions of triggered rules are combined into a single fuzzy set. In Fig. 4, the final conclusion is aggregated, by taking the union of all scaled conclusions.

Step 4: Defuzzifying overall conclusion

In many cases, the final output of an inference system is a single number. Defuzzification is a method of justifiably converting a fuzzy set into a precise value. This study utilized the center-of-gravity method, which takes the center of the area under the curve of the membership function of a fuzzy set as the answer. Figure 4 indicates that the severity score for the noise produced by the normal operation of backhoes is 53.20 (see SE_a of *a*-25 in Table 2).

3.3 Applying severity ratio to compare with standard values (SR_a)

To better interpret the outputs of fuzzy logic, all outputs are divided by the severities derived from their respective standard values, to become the severity ratios (SR_a). The standard values for emission-related environmental aspects are extracted from emission standards. For example, the standard values for TSP, noise, SO_x, NO_x, and CO are 500 mg/m^3, 70 dB(A), 650, 250, and 2,000 ppm, respectively. The severities of emission-related environmental aspects that reach standard values, which can be viewed as thresholds, are therefore designated as 100.0; other severity ratios are the proportions compared with the standard values. For example, the severity of the noise produced by the normal operation of backhoes reaching standard value is 70.80, so the severity ratio (SR_a) is computed, by 53.20/70.80, as 75.14 (see SR_a of *a*-25 in Table 2).

In this study, the SR_a for a non-emission-related environmental aspect is defined as the ratio (in percentage) of an additional amount due to improper use or operation, divided by the amount in normal situation. In another words, the amount in normal situation is viewed as a standard value. Sometimes, the value of the percentage is directly estimated by evaluators (see SR_a of *a*-3, etc. in Electronic Supplementary Material 1).

3.4 Evaluating the probability of the receptors being exposed to an aspect (P_a)

Further investigation is not required if no actual or potential pathway exists between an environmental aspect and the

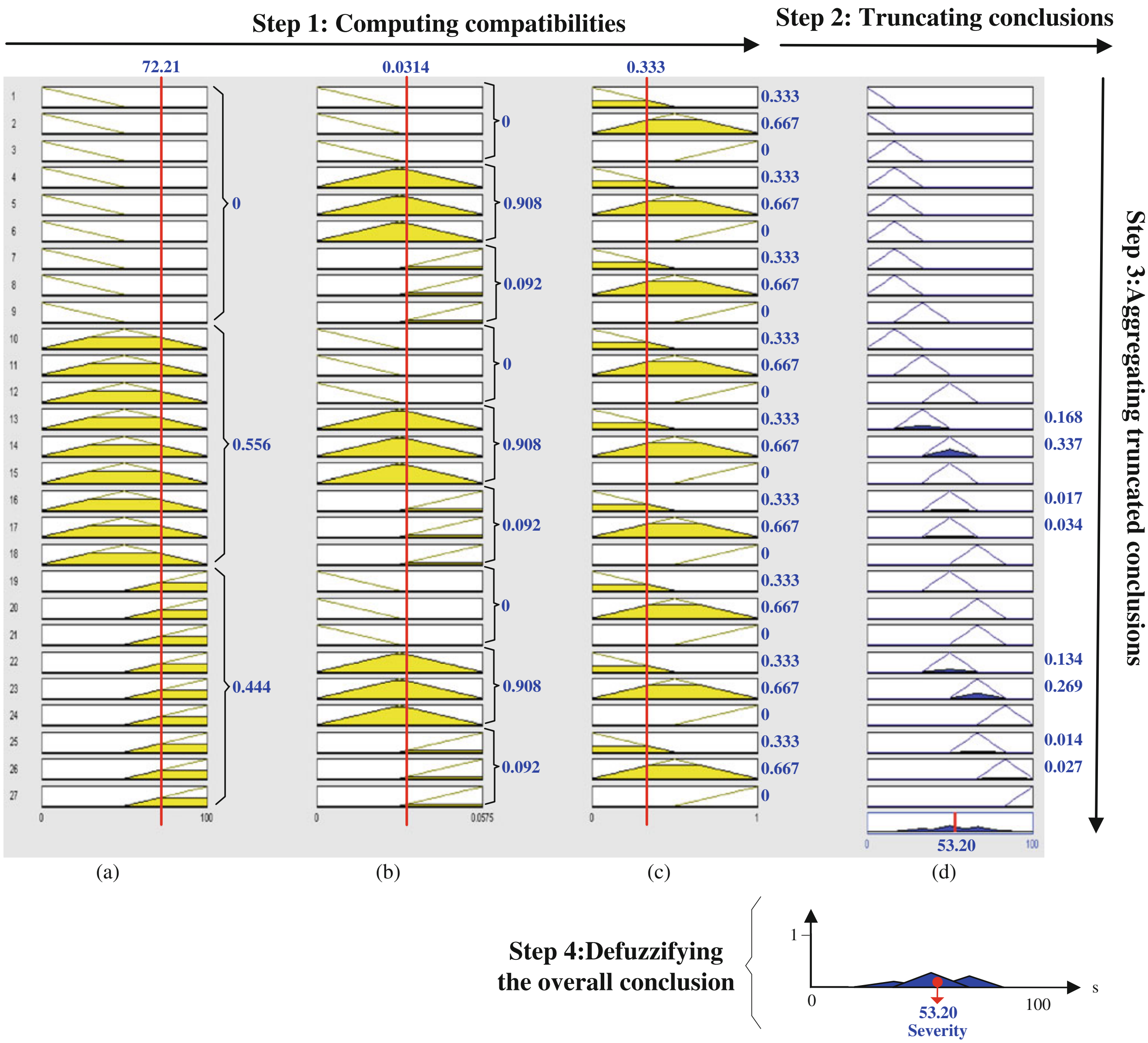


Fig. 4 Graphical representation of fuzzy logic. (**a**) Magnitude (in decibel). (**b**) Scale (in square kilometers). (**c**) Duration (in years). (**d**) Severity

receptor (DEFRA 2002). For example, heavy metal contamination of soil does not pose a risk to humans, if there are no residents near the site. Evaluating the probability of a receptor being exposed to a midpoint effect (P_a), caused by an aspect, can result in a precise number, or a probability distribution, if sufficient information is available. Otherwise, it can be assigned through expertise, or experience, which is usually fuzzy and expressed as a possibility distribution (Zadeh 1978). For example, the noise produced by the normal operation of backhoes can be a direct cause of human psychasthenia, so the probability of the receptors being exposed to the noise is subjectively estimated as "about 0.5," which is represented as a triangular fuzzy set of the 3-tuple (0.2, 0.5, 0.8).

3.5 Assessing the probability of an impact resulting from exposure to an aspect (P_i)

The probability of an impact (endpoint effect) resulting from exposure to an aspect (P_i) is related to the percentage of humans, ecosystems, crops and woods, wildlife, or fish production that sustains an impact, when exposed to an aspect. Even if exposed to the same midpoint effect, the likelihood of the impact is probabilistic and relies on the likely susceptibility of an individual receptor to the effect. Assessing P_i represents an extremely complicated task, which is plagued by uncertainty, because the relevant knowledge of toxicology, epidemiology, and ecology is still incomplete. Therefore, it

is represented as a precise number, or a probability distribution, once the relevant knowledge is available; otherwise, it can be assigned, subjectively, through expertise or experience. For example, the probability of psychasthenia resulting from exposure to the noise produced by the normal operation of backhoes is subjectively assessed as "about 0.3," which is expressed as a triangular fuzzy set of the 3-tuple, (0.1, 0.3, 0.5). A value of P_i of about 0.3 denotes that about 30 % of human exposure to the noise produced by the normal operation of backhoes will induce psychasthenia.

Figure 3 shows that all of the probabilities of receptors being exposed to aspects (P_a) and the probabilities of impacts resulting from exposure to aspects (P_i) are determined for the real situation. They are then assigned, by experts, in the form of possibility distributions, rather than probability distributions, due to insufficient information being available, as shown in Table 4.

3.6 Using the vertex method to compute risk of an impact (R)

The risk of an impact (R) is a function of three variables (SR, P_a, and P_i):

$$R = f(\mathrm{SR}_a, P_a, P_i). \tag{1}$$

Table 4 Probabilities of receptors being exposed to aspects (P_a) and the probabilities of impacts resulting from exposure to aspects (P_i)

Receptor	Pathway	P_a	Impact	P_i
Human	Climate change	(0.5, 0.8, 1.0)	Malnutrition	(0.0, 0.1, 0.2)
			Infectious diseases	(0.2, 0.3, 0.4)
			Heat stress	(0.2, 0.3, 0.4)
	Ozone depletion	(0.3, 0.6, 0.9)	Cancer	(0.2, 0.3, 0.4)
			Immunosuppression	(0.1, 0.2, 0.3)
			Cataract	(0.0, 0.1, 0.2)
	Ionizing radiation	(0.1,0.3,0.5)	Cancer	(0.6, 0.7, 0.8)
	TSP (direct effect)	(0.6,0.9,1.0)	Cardiovascular disease	(0.0, 0.1, 0.2)
			Respiratory diseases	(0.3, 0.5, 0.7)
	Noise and vibration (direct effect)	(0.2, 0.5, 0.8)	Psychasthenia	(0.1, 0.3, 0.5)
			Sleep disorders	(0.1, 0.3, 0.5)
	Photochemical smog	(0.3, 0.6, 0.9)	Respiratory diseases	(0.1, 0.3, 0.5)
	Increased tropospheric ozone concentration	(0.4, 0.7, 1.0)	Respiratory diseases	(0.2, 0.4, 0.6)
	Acidification	(0.5, 0.8, 1.0)	Human toxicity	(0.0, 0.1, 0.2)
	Ecotoxicity	(0.3, 0.6, 0.9)	Human toxicity	(0.1, 0.2, 0.3)
			Cancer	(0.1, 0.2, 0.3)
Ecosystem	Climate change	(0.5, 0.8, 1.0)	Loss of biodiversity	(0.1, 0.2, 0.3)
	Ionizing radiation	(0.0, 0.2, 0.4)	Loss of biodiversity	(0.4, 0.7, 1.0)
	Acidification	(0.4, 0.7, 1.0)	Loss of biodiversity	(0.0, 0.1, 0.2)
	Eutrophication	(0.3, 0.6, 0.9)	Loss of biodiversity	(0.0, 0.2, 0.4)
	Ecotoxicity	(0.3, 0.6, 0.9)	Loss of biodiversity	(0.1, 0.3, 0.5)
Crops and woods	Climate change	(0.5, 0.8, 1.0)	Loss of productivity of crops and woods	(0.1, 0.3, 0.5)
	Ozone depletion	(0.3, 0.6, 0.9)	Loss of productivity of crops and woods	(0.0, 0.2, 0.4)
	Increased tropospheric ozone concentration	(0.1, 0.4, 0.7)	Loss of productivity of crops and woods	(0.1, 0.3, 0.5)
	Acidification	(0.4, 0.7, 1.0)	Loss of productivity of crops and woods	(0.2, 0.4, 0.6)
Wildlife	Ozone depletion	(0.1, 0.4, 0.7)	Disappearance of species	(0.0, 0.1, 0.2)
	Increased tropospheric ozone concentration	(0.5, 0.8, 1.0)	Disappearance of species	(0.1, 0.3, 0.5)
	Acidification	(0.4, 0.7, 1.0)	Disappearance of species	(0.0, 0.2, 0.4)
	Eutrophication	(0.2, 0.5, 0.8)	Disappearance of species	(0.0, 0.2, 0.4)
Fish production	Ozone depletion	(0.5, 0.8, 1.0)	Loss of fish catch	(0.0, 0.2, 0.4)
	Acidification	(0.5, 0.8, 1.0)	Loss of fish catch	(0.0, 0.1, 0.2)
	Eutrophication	(0.4, 0.7, 1.0)	Loss of fish catch	(0.0, 0.2, 0.4)

The vertex method was proposed by Dong and Shah (1987), to compute functions of fuzzy variables, and was applied, herein, to obtain R, in Eq. (1). The vertex method is based on the α-cut technique, from fuzzy set theory, and the interval analysis. Using α-cut, each fuzzy variable characterized by a convex membership function is converted into a group of intervals associated with various α values. Intervals with the same α value, from all fuzzy variables, are processed by interval analysis. This results in an interval function, with the α value. At the α-cut level, the interval function can be denoted as follows:

$$R^\alpha = f(\mathrm{SR}_a^\alpha, P_a^\alpha, P_i^\alpha) \tag{2}$$

where

$$R^\alpha = [R_\mathrm{L}^\alpha, R_\mathrm{R}^\alpha],\ \mathrm{SR}_a^\alpha = [a_1^\alpha, b_1^\alpha],\ P_a^\alpha = [a_2^\alpha, b_2^\alpha],\ P_i^\alpha = [a_3^\alpha, b_3^\alpha]. \tag{3}$$

The interval computation is equivalent to solving a minimization problem for the lower bound and a maximization problem for the upper bound, as follows:

$$R_\mathrm{L}^\alpha = \min f(\mathrm{sr}_a, p_a, p_i),\ R_\mathrm{R}^\alpha = \max f(\mathrm{sr}_a, p_a, p_i) \tag{4}$$

such that $\mathrm{sr}_a \in [a_1^\alpha, b_1^\alpha],\ p_a \in [a_2^\alpha, b_2^\alpha],\ p_i \in [a_3^\alpha, b_3^\alpha]$..

In statistics, the notion of risk is often modeled as the expected value of an undesirable outcome. Therefore, the risk of an impact is defined as:

$$R = \mathrm{SR}_a \times P_a \times P_i \tag{5}$$

that is, R can be considered to be the fuzzy expected value of the percentage of humans, ecosystems, crops and woods, wildlife, or fish production that sustains an impact. Equation (5) becomes

$$R_\mathrm{L}^\alpha = a_1^\alpha \times a_2^\alpha \times a_3^\alpha,\ R_\mathrm{R}^\alpha = b_1^\alpha \times b_2^\alpha \times b_3^\alpha. \tag{6}$$

For example, the SR_a of the noise produced by the normal operation of backhoes is 75.14, P_a is subjectively estimated as "about 0.5 (0.2, 0.5, 0.8)" and P_i is "about 0.3 (0.1, 0.3, 0.5)," so we can obtain $R_\mathrm{L}^{0+} = 75.14 \times 0.2 \times 0.1 = 1.5028$, $R_\mathrm{R}^{0+} = 75.14 \times 0.8 \times 0.5 = 30.056$, $R_\mathrm{L}^1 = R_\mathrm{R}^1 = 75.14 \times 0.5 \times 0.3 = 11.271$, and so on. As shown in Fig. 5a, the result for R is not exact, but is very similar to a triangular fuzzy number and can be approximately represented as a triangular fuzzy set (1.503, 11.271, 30.056), which represents the fuzzy expected value of the percentage of humans that will suffer psychasthenia.

3.7 Evaluating the significance of a risk

Whether a risk is significant, it depends on the degree of human concern about the risk. As shown in part E of Fig. 3, human concerns are health, the ecosystem, resources, and, finally, environmental sustainability. This study proposes a new MCDA method, the MMCA, to evaluate the significance of a risk, according to these concerns.

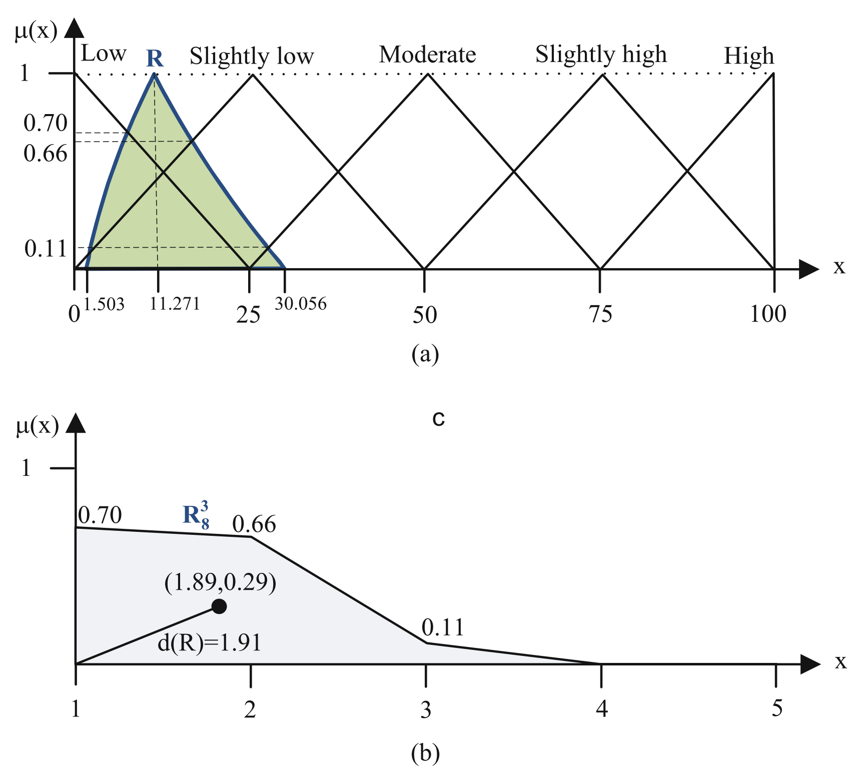


Fig. 5 Result for R, using the vertex method and its vectorization. **a** Risk of an impact. **b** Vectorized risk of an impact (noise)

3.7.1 Multi-criteria and multi-connection comprehensive assessment

The MMCA is an extension of fuzzy comprehensive assessment (Gong and Jin 2009; Kumar et al. 2011). MCCA is a multilevel network, as illustrated in Fig. 6. The goal (G) is at the top level of the network and each level, i, contains a criterion, O_k^i. The connections between two adjacent levels are network-like, rather than hierarchical, and are termed multiple connections, in this study. The connection strength between criterion, O_k^i, in the i-th level, and criterion, O_j^{i-1}, in the $(i-1)$-th level, is expressed as a weight, w_{jk}^i. Assume that criterion, O_k^i, is at the lowest level, i, then its degrees of membership to n classes are represented by a classification vector, $R_k^i = \left[r_{k1}^i\ r_{k2}^i \ldots\ldots\ldots r_{kn}^i\right]$. Once all classification vectors, R_k^i, in the level, i, multiply corresponding weights and propagate to the upper level, then R_j^{i-1} is obtained. Using this process, all classification vectors for O_k^i and G can be derived.

1. Decision framework

The first step is the decomposition of the goal G into multiple levels, with multiple criteria. Thereby, the connections between two adjacent levels are determined. The collection of all criteria in level, i, is represented by U^i, as the following equation:

$$U^i = \left\{O_1^i, O_2^i, \ldots\ldots, O_k^i, \ldots\ldots, O_q^i\right\} \tag{7}$$

where O_k^i represents the k-th criterion in level, i, and q is the number of criteria in this level.

2. Weights

All criteria in level, i, are connected to the criterion, O_j^{i-1}, in the level, $i-1$. The connection strengths are expressed by a set of weights, W_j^i, such that

$$W_j^i = \left[w_{j1}^i\ w_{j2}^i, \ldots\ldots, w_{jq}^i\right] \tag{8}$$

where w_{jk}^i indicates the weight of O_k^i, with respect to O_j^{i-1}, so the summation of w_{jk}^i is 1:

$$\sum_{k=1}^{q} w_{jk}^i = 1. \tag{9}$$

Similarly, the other sets of weights can be obtained to form a weight matrix, W^i, for the level, i, as follows:

$$W^i = \begin{bmatrix} W_1^i \\ W_2^i \\ \vdots \\ W_p^i \end{bmatrix} = \begin{bmatrix} w_{11}^i w_{12}^i \ldots\ldots\ldots\ldots w_{1q}^i \\ \mathrm{w}_{21}^{\mathrm{i}} \mathrm{w}_{22}^{\mathrm{i}} \ldots\ldots\ldots\ldots \mathrm{w}_{2\mathrm{q}}^{\mathrm{i}} \\ \vdots \qquad\qquad \vdots \\ w_{p1}^i w_{p1}^i \ldots\ldots\ldots\ldots w_{pq}^i \end{bmatrix}_{p\times q} . \tag{10}$$

However, the first level down from the goal, G, has the following weights:

$$W^1 = \left[w_1^1\ w_2^1 \ldots\ldots\ldots\ldots, w_a^1\right] \tag{11}$$

where w_j^1 indicates the weight of criterion, O_j^1, with respect to G, and a indicates the number of criteria in the first level.

3. Vectorization

For the criterion, O_k^i, in the lowest level, i, its fuzzy score, R, is vectorized as a classification vector, R_k^i, as follows.

$$R_k^i = \left[r_{k1}^i r_{k2}^i \ldots\ldots, r_{km}^i, \ldots\ldots r_{kn}^i\right] \tag{12}$$

where r_{km}^i indicates the degree of the membership of R that belongs to fuzzy class, m. Similarly, the other set of classification vectors can also be derived, to form a classification matrix, R^i, for the level, i, as follows:

$$R^i = \begin{bmatrix} R_1^i \\ R_2^i \\ \vdots \\ R_q^i \end{bmatrix} = \begin{bmatrix} r_{11}^i r_{12}^i \ldots\ldots\ldots\ldots\ldots r_{1n}^i \\ r_{21}^i r_{22}^i \ldots\ldots\ldots\ldots\ldots r_{2n}^i \\ \vdots \qquad\qquad \vdots \\ r_{q1}^i r_{q2}^i \ldots\ldots\ldots\ldots\ldots r_{qn}^i \end{bmatrix}_{q\times n} . \tag{13}$$

4. Evaluation

For the upper level, $i-1$, the classification matrix, R^{i-1}, is the product of W^i and R^i, as the following equation illustrates:

$$R^{i-1} = W^i \times R^i \tag{14}$$

That is,

$$R^{i-1} = \begin{bmatrix} R_1^{i-1} \\ R_2^{i-1} \\ \vdots \\ R_p^{i-1} \end{bmatrix} = \begin{bmatrix} r_{11}^{i-1} r_{12}^{i-1} \ldots\ldots\ldots\ldots\ldots r_{1n}^{i-1} \\ r_{21}^{i-1} r_{22}^{i-1} \ldots\ldots\ldots\ldots\ldots r_{2n}^{i-1} \\ \vdots \qquad\qquad \vdots \\ r_{p1}^{i-1} r_{p2}^{i-1} \ldots\ldots\ldots\ldots\ldots r_{pn}^{i-1} \end{bmatrix}_{p\times n}$$
$$= \begin{bmatrix} w_{11}^i w_{12}^i \ldots\ldots\ldots\ldots w_{1q}^i \\ w_{21}^i w_{22}^i \ldots\ldots\ldots\ldots w_{2q}^i \\ \vdots \qquad\qquad \vdots \\ w_{p1}^i w_{p2}^i \ldots\ldots\ldots\ldots w_{pq}^i \end{bmatrix}_{p\times q} \begin{bmatrix} r_{11}^i r_{12}^i \ldots\ldots\ldots\ldots\ldots r_{1n}^i \\ r_{21}^i r_{22}^i \ldots\ldots\ldots\ldots\ldots r_{2n}^i \\ r_{31}^i r_{32}^i \ldots\ldots\ldots\ldots\ldots r_{3n}^i \\ \vdots \qquad\qquad \vdots \\ r_{q1}^i r_{q2}^i \ldots\ldots\ldots\ldots\ldots r_{qn}^i \end{bmatrix}_{q\times n} \tag{15}$$

where r_{jm}^{i-1} is computed by the following equation:

$$r_{jm}^{i-1} = \sum_{k=1}^{q} \left(w_{jk}^i \times r_{km}^i\right) \tag{16}$$

and the j-th row, R^{i-1}, of R_j^{i-1}, is the classification results for O_j^{i-1} and can be represented as follows:

$$R_j^{i-1} = \left[r_{j1}^{i-1}\ r_{j2}^{i-1} \ldots\ldots\ldots\ldots r_{jn}^{i-1}\right]. \tag{17}$$

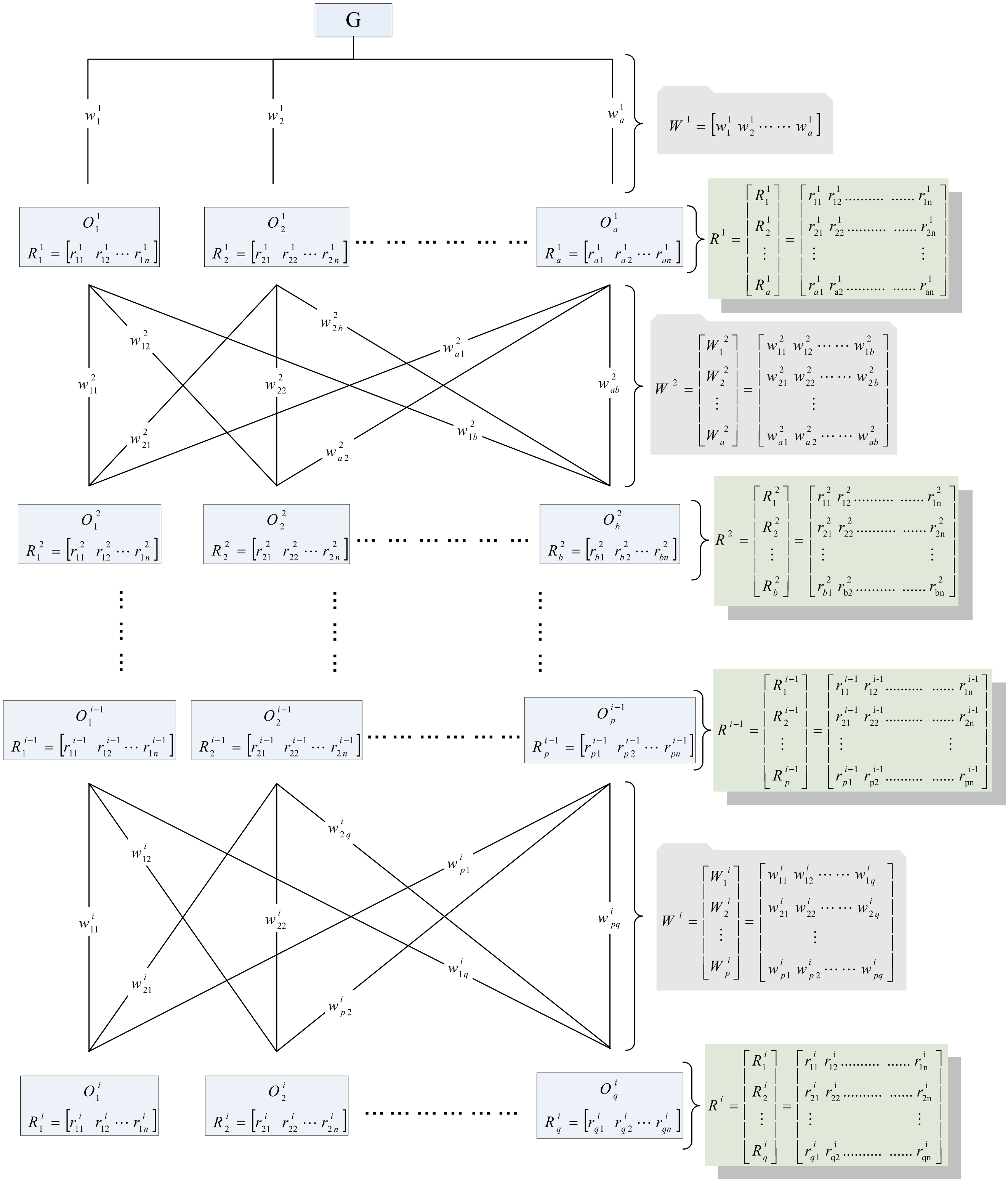


Fig. 6 Structure of multi-criteria and multi-connection comprehensive assessment

Each criterion, O_k^i, has its own classification vector, R_k^i, which is considered as the evaluation result.

5. Defuzzification

These classification vectors, R_k^i, shown in Fig. 5b, are fuzzy numbers and they are difficult to rank, accurately. This study proposes a distance method, to defuzzify fuzzy numbers, using the ranking method of Cheng (1998) and

Chu and Tsao (2002). In Fig. 5b, the centroid, $(\bar{x},\bar{y})$, of R_k^i, is calculated using the following equation:

$$\bar{x} = \frac{\int x \times B(x)dx}{\int B(x)dx} \quad \bar{y} = \frac{\int y \times B(y)dy}{\int B(y)dy} \tag{18}$$

where $B(x)$ (or $B(y)$) are the membership functions of R_k^i. The distance from the centroid to the origin is computed by

$$d(R) = \sqrt{\bar{x}^2 + \bar{y}^2}. \tag{19}$$

3.7.2 An example

1. Decision framework

The decision framework for this study is shown in parts D (impact) and E (concern) of Fig. 3. The goal, G={environmental sustainability}, is decomposed into two levels, with multiple criteria, and the connections between two adjacent levels form a hierarchy. The first level has three criteria, representing human concerns; that is U^1={human health, ecosystem resource}. The second level has 15 criteria to indicate potential impact, that is, U^2={malnutrition, infectious diseases, heat stress… loss of fish catch}.

2. Weights

A total of 13 experts, either from the Department of Environmental Engineering of Da-Yeh University (Taiwan) or from the Department of Safety, Health and Environmental Engineering of Ming Chi University of Technology (Taiwan), were asked for their opinions, via a questionnaire, to determine the weight matrix, W^i. The results are shown in Table 5. The averages of their judgments form W^2 and W^1 are as follows:

$$W^2 = \begin{bmatrix} 0.07 & 0.08 & 0.08 & 0.10 & 0.07 & 0.10 & 0.11 & 0.08 & 0.09 & 0.10 & 0.12 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.52 & 0.48 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.51 & 0.49 \end{bmatrix} \tag{20}$$

Table 5 Expert opinions on the weights in the decision framework

	Impact	Expert opinion														Normalized weight
		1	2	3	4	5	6	7	8	9	10	11	12	13	Average	
Human heath	Malnutrition	9	6	5	7	5	3	5	5	10	8	2	5	2	5.54	0.07
	Infectious diseases	6	4	8	5	6	5	8	2	10	9	5	9	3	6.15	0.08
	Heat stress	9	7	3	5	7	1	8	2	10	8	5	7	5	5.92	0.08
	Cancer	10	8	10	9	6	10	9	9	10	9	10	8	9	9.00	0.12
	Immunosuppression	9	7	9	7	8	4	8	7	10	9	7	8	7	7.69	0.10
	Cataract	9	2	5	4	5	6	8	3	10	7	7	5	2	5.62	0.07
	Cardiovascular disease	10	8	10	6	9	10	8	7	10	7	6	6	7	8.00	0.10
	Psychasthenia	7	3	8	5	7	2	7	6	10	9	8	8	9	6.85	0.09
	Sleep disorders	4	5	8	5	6	4	7	3	10	9	5	9	8	6.38	0.08
	Respiratory diseases	10	8	9	7	10	7	8	8	10	7	10	9	10	8.69	0.11
	Human toxicity	7	7	8	10	5	3	8	8	10	10	9	9	7	7.77	0.10
Ecosystem	Loss of biodiversity	10	8	10	8	8	9	8	7	9	10	7	6	9	8.38	0.52
	Disappearance of species	9	8	9	9	6	3	7	7	9	10	9	8	6	7.69	0.48
Resource	Loss of productivity of crops and woods	9	6	8	7	7	6	9	6	9	8	9	7	8	7.62	0.34
	Loss of fish catch	9	6	8	7	7	6	7	6	9	8	9	7	6	7.31	0.33
	Resource depletion	10	8	7	8	7	7	6	8	9	9	10	6	8	7.24	0.33
Environmental sustainability	Human heath	5	8	10	8	9	9	9	7	10	8	7	8	8	8.15	0.33
	Ecosystem	10	8	10	9	8	7	9	7	9	10	10	9	5	8.54	0.34
	Resource	8	7	10	8	7	8	9	6	9	10	8	7	8	8.08	0.33

$$W^1 = [0.33 \quad 0.34 \quad 0.33]. \tag{21}$$

3. Vectorization

For example, the risk of the impact, R, of the noise produced by the normal operation of backhoes, which causes humans to suffer psychasthenia, as shown in Fig. 5a, can be transformed into the vectorized risk of impact, $R_8^3 = \{0.70\ 0.66\ 0.11\ 0\ 0\}$, as shown in Fig. 5b. Meanwhile, the R of the noise produced by the normal operation of backhoes, which causes humans to suffer sleep disorders, is also transformed into the vectorized risk of impact, $R_9^3 = \{0.70\ 0.66\ 0.11\ 0\ 0\}$. The other vectorized risk of impact, R_i^3, resulting from the noise produced by the normal operation of backhoes, is a zero vector.

Therefore, R^3 is

$$R^3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0.70 & 0.66 & 0.11 & 0 & 0 \\ 0.70 & 0.66 & 0.11 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{23}$$

4. Evaluation

For the upper levels, the classification matrices, R^2 and R^1, are computed, as follows:

$$R^2 = W^2 \times R^3 = \begin{bmatrix} 0.12 & 0.11 & 0.02 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{24}$$

$$R^1 = [0.04\ 0\ 03\ 0.01\ 0\ 0] \tag{25}$$

5. Defuzzification

Using the distance method, the fuzzy numbers in R_k^i can be defuzzified, as: $d(R_8^3) = d(R_9^3) = 1.91$ (see *a*-25 in Table 6); $d(R_1^2) = 1.89$ (see *a*-25 in Table 7); and $d(R^1) = 1.89$ (see *a*-25 in Table 8).

4 Results and discussions

4.1 Results

The inferred severities of selected environmental aspects (SE_a), as listed in the fourth to ninth columns of Table 2 (for full version please refer to Electronic Supplementary Material 1), are determined by their magnitudes, scales, and durations, using fuzzy logic. Furthermore, using the severity ratio (SR_a), the inferred severities of all environmental aspects can be compared with the results of the standard values, as shown in the last column of Table 2. According to the results for SR_a, the aspects, "*a*-25 normal operation of backhoes produces noise," "*a*-4 A5 winnowing machines cause noise," "*a*-16 B3 winnowing machines produce noise," "*a*-2 A3 918 trommel screens produce noise," "*a*-16 B2 125 trommel screens generate noise," and "*a*-63 friction between bucket and ground friction produces noise," are relatively severe and are singly underlined, in Table 2, because their magnitudes are very close to the standard values; the rest of the SR_a values are acceptable.

In accordance with Fig. 2, the impacts (endpoint effects) caused by environmental aspects, via various exposure pathways, are summarized in the third column of Table 6. In this case study, the risk of an impact (R) is defined as the product of SE_a (Table 2), P_a (Table 4), and P_i (Table 4). The vertex method is then used to compute R, when any of its factors are fuzzy, so the output is also a fuzzy number. The vectorized risks of impacts, R_i^3, and their defuzzification (the distance from the centroid of R_i^3 to the origin), $d(R_i^3)$, are subsequently calculated, as shown in the last two columns of Table 6 (for full version please refer to Electronic Supplementary Material 5). According to the results for R_i^3, the psychasthenia and sleep disorders, caused by "*a*-25 normal operation of backhoes produces noise," "*a*-4 A5 winnowing machines cause noise," and "*a*-16 B3 winnowing machines produce noise," are the top six impacts and are singly underlined in Table 6.

With reference to Fig. 3, the concerns caused by environmental aspects, through various impacts, are summarized in the third column of Table 7. In this case study, the vectorized risks of impacts, R_i^2, are calculated by the MMCA and their defuzzification, $d(R_i^2)$, is subsequently completed, as shown in the fourth and fifth columns of Table 7 (for full version please refer to Electronic Supplementary Material 6). According to the results for R_i^2, all concerns are for human health and the top three aspects are "*a*-25 normal operation of backhoes produces noise," "*a*-4 A5 winnowing machines cause noise," and "*a*-16 B3 winnowing machines produce noise," which are singly underlined in Table 7. These are the environmental aspects most urgently in need of improvement. The final values for environmental sustainability, as shown in Table 8 (for full

Table 6 Risk evaluations of environmental impacts, for a waste-recycling factory

No.	Environmental aspect	Impact	Vectorized risk of impact R_i^3	$d(R_i^3)$
a-1	A3 918 trommel screens generate TSP	Cardiovascular disease	[0.97 0.09 0.00 0.00 0.00]	1.47^{32}
		Respiratory diseases	[0.84 0.28 0.00 0.00 0.00]	1.62^{18}
a-2	A3 918 trommel screens produce noise	Psychasthenia	[0.73 0.61 0.03 0.00 0.00]	1.81^{8}
		Sleep disorders	[0.73 0.61 0.03 0.00 0.00]	1.81^{8}
a-4	A5 winnowing machines cause noise	Psychasthenia	[0.72 0.63 0.05 0.00 0.00]	$\underline{1.84}^{3}$
		Sleep disorders	[0.72 0.63 0.05 0.00 0.00]	$\underline{1.84}^{3}$
a-5	A5 winnowing machines generate TSP	Cardiovascular disease	[0.95 0.13 0.00 0.00 0.00]	1.50^{30}
		Respiratory diseases	[0.78 0.39 0.00 0.00 0.00]	1.69^{16}
a-7	A7 crushers generate TSP	Cardiovascular disease	[0.97 0.08 0.00 0.00 0.00]	1.46^{34}
		Respiratory diseases	[0.86 0.25 0.00 0.00 0.00]	1.60^{20}
a-13	B2 125 trommel screens produce TSP	Cardiovascular disease	[0.97 0.09 0.00 0.00 0.00]	1.47^{32}
		Respiratory diseases	[0.84 0.28 0.00 0.00 0.00]	1.62^{18}
a-14	B2 125 trommel screens generate noise	Psychasthenia	[0.73 0.61 0.03 0.00 0.00]	1.81^{8}
		Sleep disorders	[0.73 0.61 0.03 0.00 0.00]	1.81^{8}
a-16	B3 winnowing machines produce noise	Psychasthenia	[0.72 0.63 0.05 0.00 0.00]	$\underline{1.84}^{3}$
		Sleep disorders	[0.72 0.63 0.05 0.00 0.00]	$\underline{1.84}^{3}$
a-17	B3 winnowing machines cause TSP	Cardiovascular disease	[0.97 0.08 0.00 0.00 0.00]	1.46^{34}
		Respiratory diseases	[0.86 0.25 0.00 0.00 0.00]	1.60^{20}
a-19	Transporting and dumping materials by vehicles produce TSP	Cardiovascular disease	[0.92 0.20 0.00 0.00 0.00]	1.56^{28}
		Respiratory diseases	[0.66 0.59 0.00 0.00 0.00]	1.78^{14}
a-25	Normal operation of backhoes produces noise	Psychasthenia	[0.70 0.66 0.11 0.00 0.00]	$\underline{1.91}^{1}$
		Sleep disorders	[0.70 0.66 0.11 0.00 0.00]	$\underline{1.91}^{1}$
a-26	Normal operation of backhoes causes TSP	Cardiovascular disease	[0.97 0.07 0.00 0.00 0.00]	1.45^{39}
		Respiratory diseases	[0.87 0.24 0.00 0.00 0.00]	1.59^{25}
a-32	Digging mixtures into hoppers by backhoes generates TSP	Cardiovascular disease	[0.97 0.08 0.00 0.00 0.00]	1.46^{34}
		Respiratory diseases	[0.86 0.25 0.00 0.00 0.00]	1.60^{20}
a-34	Drying moving lines by drying vehicles generates TSP	Cardiovascular disease	[0.97 0.07 0.00 0.00 0.00]	1.45^{38}
		Respiratory diseases	[0.87 0.24 0.00 0.00 0.00]	1.59^{25}
a-40	Stirring up finished or semifinished products in storage area causes TSP	Cardiovascular disease	[0.90 0.26 0.00 0.00 0.00]	1.60^{20}
		Respiratory diseases	[0.58 0.71 0.00 0.00 0.00]	1.83^{7}
a-42	Loading or transporting finished or semifinished products generates TSP	Cardiovascular disease	[0.93 0.17 0.00 0.00 0.00]	1.54^{29}
		Respiratory diseases	[0.71 0.51 0.00 0.00 0.00]	1.74^{15}
a-48	Removal and transportation of plastic waste produce TSP	Cardiovascular disease	[0.97 0.07 0.00 0.00 0.00]	1.45^{39}
		Respiratory diseases	[0.87 0.23 0.00 0.00 0.00]	1.59^{25}
a-54	Transporting debris by conveyor causes TSP	Cardiovascular disease	[0.97 0.08 0.00 0.00 0.00]	1.46^{34}
		Respiratory diseases	[0.86 0.25 0.00 0.00 0.00]	1.60^{20}
a-57	Transporting finished or semifinished products by scrapers produces TSP	Cardiovascular disease	[0.95 0.13 0.00 0.00 0.00]	1.50^{30}
		Respiratory diseases	[0.78 0.39 0.00 0.00 0.00]	1.67^{17}
a-63	Friction between bucket and ground friction produces noise	Psychasthenia	[0.73 0.61 0.02 0.00 0.00]	1.80^{12}
		Sleep disorders	[0.73 0.61 0.02 0.00 0.00]	1.80^{12}

Superscript denotes the sequence order

version please refer to Electronic Supplementary Material 7), indicate that "*a*-25 normal operation of backhoes produces noise," "*a*-4 A5 winnowing machines cause noise," and "*a*-16 B3 winnowing machines produce noise," which are all singly underlined in Table 8, are the environmental aspects in most urgent need of improvement.

5 Discussion

The ranking of environmental aspects relies on evaluation methods. In the first case study, Chen (2009) considered the frequency of occurrence of aspects, impact severity, and other major criteria, such as technology, cost, public image,

Table 7 Risk evaluations of concerns, for a waste-recycling factory

No.	Environmental aspect	Concern	Vectorized risk of concern R_i^2	$d(R_i^2)$
a-1	A3 918 trommel screens generate TSP	Human heath	[0.19 0.04 0.00 0.00 0.00]	1.53^{12}
a-2	A3 918 trommel screens produce noise	Human heath	[0.12 0.10 0.01 0.00 0.00]	1.79^{4}
a-4	A5 winnowing machines cause noise	Human heath	[0.12 0.11 0.01 0.00 0.00]	$\underline{1.81}^{2}$
a-5	A5 winnowing machines generate TSP	Human heath	[0.19 0.06 0.00 0.00 0.00]	1.59^{10}
a-7	A7 crushers generate TSP	Human heath	[0.20 0.04 0.00 0.00 0.00]	1.51^{14}
a-13	B2 125 trommel screens produce TSP	Human heath	[0.19 0.04 0.00 0.00 0.00]	1.53^{12}
a-14	B2 125 trommel screens generate noise	Human heath	[0.12 0.10 0.01 0.00 0.00]	1.79^{4}
a-16	B3 winnowing machines produce noise	Human heath	[0.12 0.11 0.01 0.00 0.00]	$\underline{1.81}^{2}$
a-17	B3 winnowing machines cause TSP	Human heath	[0.20 0.04 0.00 0.00 0.00]	1.51^{14}
a-19	Transporting and dumping materials by vehicles produce TSP	Human heath	[0.17 0.09 0.00 0.00 0.00]	1.67^{8}
a-25	Normal operation of backhoes produces noise	Human heath	[0.12 0.11 0.02 0.00 0.00]	$\underline{1.89}^{1}$
a-26	Normal operation of backhoes causes TSP	Human heath	[0.20 0.03 0.00 0.00 0.00]	1.51^{14}
a-32	Digging mixtures into hoppers by backhoes generates TSP	Human heath	[0.20 0.04 0.00 0.00 0.00]	1.51^{14}
a-34	Drying moving lines by drying vehicles generates TSP	Human heath	[0.20 0.03 0.00 0.00 0.00]	1.51^{14}
a-40	Stirring up finished or semifinished products in storage area causes TSP	Human heath	[0.16 0.11 0.00 0.00 0.00]	1.72^{7}
a-42	Loading or transporting finished or semifinished products generates TSP	Human heath	[0.18 0.07 0.00 0.00 0.00]	1.64^{9}
a-48	Removal and transportation of plastic waste produce TSP	Human heath	[0.20 0.03 0.00 0.00 0.00]	1.51^{14}
a-54	Transporting debris by conveyor causes TSP	Human heath	[0.20 0.04 0.00 0.00 0.00]	1.51^{14}
a-57	Transporting finished or semifinished products by scrapers produces TSP	Human heath	[0.19 0.06 0.00 0.00 0.00]	1.59^{10}
a-63	Friction between bucket and ground friction produces noise	Human heath	[0.12 0.10 0.00 0.00 0.00]	1.77^{6}

Superscript denotes the sequence order

Table 8 Risk evaluation for environmental sustainability, for a waste-recycling factory

No.	Environmental aspect	Vectorized risk of sustainability R_i^1	$d(R_i^1)$	FSM
a-1	A3 918 trommel screens generate TSP	[0.06 0.01 0.00 0.00 0.00]	1.52^{12}	$\underline{\underline{80}}^{1}$
a-2	A3 918 trommel screens produce noise	[0.04 0.03 0.00 0.00 0.00]	1.79^{4}	10^{15}
a-4	A5 winnowing machines cause noise	[0.04 0.04 0.00 0.00 0.00]	$\underline{1.82}^{2}$	10^{15}
a-5	A5 winnowing machines generate TSP	[0.06 0.02 0.00 0.00 0.00]	1.58^{10}	$\underline{\underline{60}}^{2}$
a-7	A7 crushers generate TSP	[0.06 0.01 0.00 0.00 0.00]	1.51^{14}	30^{6}
a-13	B2 125 trommel screens produce TSP	[0.06 0.01 0.00 0.00 0.00]	1.52^{12}	$\underline{\underline{60}}^{2}$
a-14	B2 125 trommel screens generate noise	[0.04 0.03 0.00 0.00 0.00]	1.79^{4}	10^{15}
a-16	B3 winnowing machines produce noise	[0.04 0.04 0.00 0.00 0.00]	$\underline{1.82}^{2}$	10^{15}
a-17	B3 winnowing machines cause TSP	[0.06 0.01 0.00 0.00 0.00]	1.51^{14}	10^{15}
a-19	Transporting and dumping materials by vehicles produce TSP	[0.06 0.03 0.00 0.00 0.00]	1.66^{8}	$\underline{\underline{60}}^{2}$
a-25	Normal operation of backhoes produces noise	[0.04 0.03 0.01 0.00 0.00]	$\underline{1.89}^{1}$	10^{15}
a-26	Normal operation of backhoes causes TSP	[0.06 0.01 0.00 0.00 0.00]	1.50^{18}	20^{8}
a-32	Digging mixtures into hoppers by backhoes generates TSP	[0.06 0.01 0.00 0.00 0.00]	1.51^{14}	20^{8}
a-34	Drying moving lines by drying vehicles generates TSP	[0.06 0.01 0.00 0.00 0.00]	1.50^{18}	10^{15}
a-40	Stirring up finished or semifinished products in storage area causes TSP	[0.05 0.03 0.00 0.00 0.00]	1.71^{7}	20^{8}
a-42	Loading or transporting finished or semifinished products generates TSP	[0.06 0.02 0.00 0.00 0.00]	1.63^{9}	$\underline{\underline{60}}^{2}$
a-48	Removal and transportation of plastic waste produce TSP	[0.06 0.01 0.00 0.00 0.00]	1.49^{20}	10^{15}
a-54	Transporting debris by conveyor causes TSP	[0.06 0.01 0.00 0.00 0.00]	1.51^{14}	20^{8}
a-57	Transporting finished or semifinished products by scrapers produces TSP	[0.06 0.02 0.00 0.00 0.00]	1.58^{10}	30^{6}
a-63	Friction between bucket and ground friction produces noise	[0.04 0.03 0.00 0.00 0.00]	1.78^{6}	10^{15}

Superscript denotes the sequence order

FSM frequency, severity, and major criteria method (Chen 2009)

and safety and health. His scoring methods involved multiplication of these, together with some decision tables, as shown in Table 1. Chen's method concluded a different order for the environmental aspects than that obtained by this study, as shown in the last column of Table 8. The principle environmental aspect was "*a*-1 A3 918 trommel screens generate dust," followed by "*a*-5 A5 winnowing machines generate dust," "*a*-13 B2 125 trommel screens produce dust," "*a*-19 transporting and dumping materials by vehicles produce dust," and "*a*-42 loading or transporting finished or semifinished products generates dust"—all of which are doubly underlined in Table 7. Although Chen considered more significance criteria, both the evaluation of the severity of an environmental impact and the scoring methods lacked a sound theoretical basis and tended to be over-subjective.

6 Conclusions

This study proposed an integrated tool, combining RA, LCA, and MMCA, in order to determine the probabilistic causality of the aspect–pathway–receptor–impact relationships, to enhance the theoretical foundation and to strengthen decision-making, when assessing environmental aspects for an EMS, via the following steps: incorporation of the LCA concept for the identification of aspect–pathway–receptor–impact relationships, use of fuzzy logic for aspect assessment, use of a severity ratio, for comparison with standard values, evaluation of the probability of a receptor being exposed to a midpoint effect, assessment of the probability of an impact resulting from exposure to the aspect, use of the vertex method, to compute the risk of the impact, and evaluation of the significance of the risk, through MMCA. The proposed model was also verified through a waste-recycling factory, and the results showed that the proposed method successfully prioritizes the environmental aspects, on a more solid theoretical basis. It should be noted that the case study only demonstrated the use of environmental assessment criteria in MMCA. But MMCA can simultaneously embrace non-environmental assessment criteria such as legal requirements, interested party demand, cost, image, etc.

This study encountered several difficulties and further work is still required, to overcome these. The first was the determination of the probabilities of midpoint effects (e.g., climate change), resulting from environmental aspects (e.g., CO_2 emission). This type of probability was neglected in this study because some of them are still subject to scientific debate. The second difficulty was in gathering sufficient epidemiological studies to allow accurate determination of the probability of an impact resulting from exposure to an aspect. Subjective judgment was used when assigning probabilities to these impacts. The third difficulty was the appropriateness of crisp weights in MMCA, resulting from averaging expert opinions. MMCA can be extended to fuzzy weights in the future work, since fuzzy numbers are able to simultaneously describe the degree of consistency of the expert judgments. The last difficulty was associated with the popularization of the integrated approach in business practice. To use the proposed approach, environmental managers have to learn the knowledge of fuzzy logic, risk assessment, life cycle assessment, and multi-criteria decision analysis; besides, they also have to overcome the computational complexity inherent in fuzzy computation. However, the difficulty can be conquered if a software is implemented to perform the environmental aspects assessment based on the proposed approach.

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